...uses, Circuit Breakers
and other
Electrical Safety Devices

by
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ELECTRICAL SAFETY DEVICES

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PREFACE

The object of the author in preparing this booklet is to explain as clearly and simply as possible the construction and operation of the principal safety devices used in connection with electrical machinery. Such devices are of vital importance in the successful operation of electrical equipment, and a clear understanding of them on the part of the operating engineer and the electrician is highly desirable.

The devices discussed here may be divided into two classes: First, those which afford positive protection against abnormal conditions of current or pressure, such as the various forms of fuses, circuit-breakers and lightning arresters. Second, those which tend to correct any unusual conditions, such as the different forms of regulators. Those of the first class are purely protective, those of the second are regulative, and thus prevent dangerous conditions from arising.

There is sometimes a tendency on the part of those who have to do with the operation of electrical equipment to regard the safety device as a necessary evil. It is hoped that a careful reading of the following pages will make plain the important function of such equipment, and induce the man in charge to give it his very best attention. Only those protective devices which are found in almost every electrical plant are

discussed, and for this reason it is not claimed that the whole field has been covered. It is believed that if the operator of electrical machinery has a clear understanding of fuses, circuit-breakers, lightning arresters and the different forms of regulators, he will have a greater respect for protective devices in general. If this is the result, the preparation of these pages will have been well worth while.

The author wishes to extend his thanks to the various manufacturers of protective equipment who have supplied many of the illustrations used. Acknowledgment has also been made in the text whenever possible.

JAMES C. PEEBLES.

Chicago, May 19, 1913.

Electrical Safety Devices

CHAPTER I.

In all machinery designed for the generation or utilization of power, the importance of automatic safety devices has been recognized from the beginning. Thus, the advent of the safety valve occurred at practically the same time as that of the steam boiler, and the governor for controlling the speed of a steam engine was developed as an important step in the design of the prime mover itself. The same is true in all power machinery: safety devices for the protection of the equipment from as many sources of injury as possible are always used.

The wide application of electricity to many kinds of industry has led to the development of a large variety of electrical safety devices, designed for the protection of equipment using this form of energy. The chief source of danger to electrical machinery is probably to be found in an abnormally large flow of current, greater than that for which the equipment is designed. This has led to the development of protective devices which automatically open the circuit whenever the current exceeds a certain safe maximum.

Early experiments with electricity soon disclosed the fact that a small wire may be fused by the heat generated by an electric current. Thus, if such a piece of wire be introduced into an electric circuit, it will serve to protect the rest of the circuit when

the current becomes excessive, by being destroyed itself. Thus the thermal action of the current can be used as a means of protection. Another method of opening a circuit is found in the magnetic properties of the current, which make possible the design of a mechanical device, allowing for the passage of the normal current but operating instantly when the current becomes excessive. The thermal property of the current has made possible the development of the fuse as a protective device, while the magnetic property has been responsible for the mechanical circuit-breaker.

Fuses.

When damage occurs to electrical equipment it is due in the great majority of cases to overheating. It is the thermal action of the current which causes the trouble, and it is exactly this same effect upon which the fuse depends for its action. Thus the fuse is particularly well suited for a protecting device, because it forms a part of the circuit and partakes of all the characteristics of the same. Its temperature rises and falls with that of the other conductors in the circuit, and it opens promptly when enough heat has been generated to become dangerous.

The first fuses used consisted merely of a small piece of copper wire introduced into the circuit, which fused when the current became excessive. On account of the relatively high melting point of copper, dangerous temperatures were reached when the copper fuse melted. Thus the copper fuse was never seriously considered. Lead and many of its alloys have comparatively low melting points, and hence are more adaptable for fuse construction. The method of application was simply to connect this piece of lead alloy wire into the circuit. To do this various kinds of cut-out bases were designed of porcelain or slate, which provided screw terminals to which the ends of

the fuse wire could be connected. Later a copper-tipped link was used instead of a simple piece of fuse wire, which provided for better connection at the cut-out terminals.

When such a fuse is melted by the heating action of the current, globules of molten lead are scattered about. If the fuse has been melted by a large, sudden increase in the current, some of the metal may be vaporized, causing an explosive action which may throw this molten metal a considerable distance. If this occurs near unprotected woodwork or other combustible material, fire may result. It is quite probable that in the earlier stages of the electrical industry fires have frequently started from this very cause.

The next step in the course of development was to enclose the fuse in some kind of a covering which would prevent the scattering of molten metal when the wire fused. A great amount of work has been done along this line, and many patents have been issued in this country and abroad, covering a variety of designs. One of the earliest patents on an enclosed fuse was issued to Edison in 1880. Fig. 1 gives a sketch of this fuse, from which it will be seen to consist merely of a piece of lead wire introduced into a gap in the circuit and surrounded by a protecting sheath. The wire inside the sheath was surrounded with air, which failed to prevent the explosive action when the fuse melted. It was, of course, an improvement on the bare wire, but fell very far short of a satisfactory enclosed fuse.

To further reduce the effects of explosive action, it was proposed to fill the protecting sheath or tube with a chemically inert powder. This was found to meet the conditions satisfactorily, and practically all modern enclosed fuses are now made in this way. The efficiency of the fuse depends to a very large extent on the qualities of this filler. In addition to being

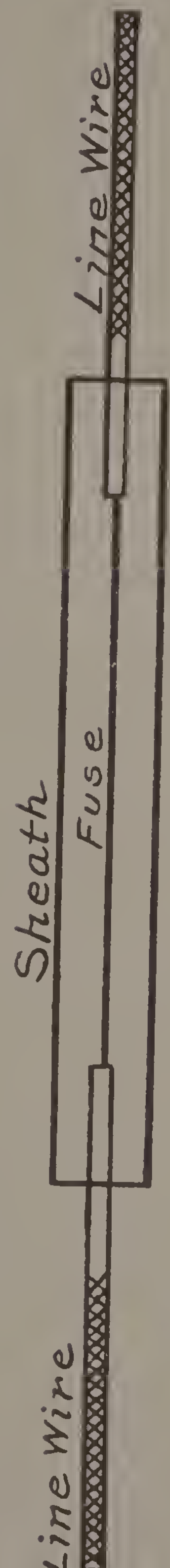

Fig. 1.

chemically inert it must be unaffected by atmospheric moisture. If the filler tends to set under the action of moisture, it virtually forms a hard casing around the fuse wire which keeps it in position even after the fusing temperature has been reached. Also, the filler must be very porous, to provide for the escape of the gases generated by the operation of the fuse. Fuse manufacturers have now succeeded in producing a powder filling which meets these requirements.

Fig. 2 shows a section of an enclosed fuse which is used on circuits of relatively low current-carrying capacity. In the figure, A is a small air drum surrounding the middle portion of the fuse wire, which

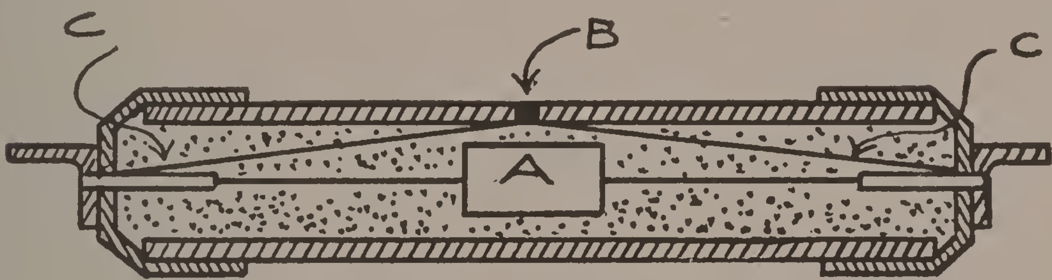

FIG. 2.

has its section somewhat reduced at this point to insure that the fuse will melt first inside the drum. The object of this form of construction is to produce a fuse in which the rise in temperature shall be proportional to the current flowing through it. The fact that the air within the drum is a very poor conductor of heat causes the fuse to heat rapidly, rendering the blowing point practically constant for any given overload. On the other hand, if the air drum is not used and the fuse wire is surrounded by the filler throughout its entire length, the rapid conduction of heat through the powder causes the blowing time for a given overload to vary within wide limits. This results from the fact that the ability of the porous powder to dissipate heat varies almost as its temperature.

Thus the blowing time for a given overload depends upon the **rate of heat conduction** through the filler, and not upon the **duration of the overload.**

C in the figure is a small fuse wire which is shunted across the main fuse. B is a small hole drilled through the protecting tube. The resistance of the shunt wire C is large as compared with that of the main fuse, hence under normal conditions of operation it carries very little current. However, when the main fuse blows, the shunt receives all the current, causing it to open up immediately. Through the small hole B it is possible to see when the shunt has been burned out. This device is known as the indicator, which enables an observer to tell at a glance whether or not any particular fuse is good or is "blown."

As the voltage of the system and the current capacity of the fuse increase, the fuse element can no longer be made of a cylindrical wire, but must be made in the form of a flat link, as shown in Fig. 3.

This link is placed inside the tube in a manner similar to that shown in Fig. 2. It has much greater surface for a given section than a wire, and hence will dissipate heat more rapidly. This is an important point under conditions of extreme short circuit where

Fig. 3.

a large amount of heat is generated very suddenly. In still larger fuses a multiple-link arrangement is used, in which two or more links are connected in parallel. On account of the large radiating surface which the multiple-link arrangement presents, the amount of metal used can be reduced. Thus the heat developed passes off rapidly, and since less metal vapor is formed it can be dissipated more readily without exploding the tube.

In all well-made enclosed fuses the tube is made of vulcanized fiber, never of paper. A paper tube swells and disintegrates under the action of moisture and renders the fuse practically useless.

Since the introduction of the enclosed fuse in 1890 a number of companies have engaged in its manufacture. These manufacturers also turned out a line of cut-outs to accommodate their fuses, but unfortunately there was no agreement among them as to standards covering dimensions and details of design. The result was that a fuse made by one manufacturer would not fit the cut-out made by another; in short, there was no interchangeability among the products of the various makers. This lack of standards caused great inconvenience and confusion, so much so that the National Board of Fire Underwriters took up the matter with the various manufacturers. Standard designs and dimensions were then agreed upon for all enclosed fuses and cut-outs, so that complete interchangeability resulted. Complete fuse equipment can now be obtained which conforms to these National Electric Code specifications, as they are called.

Two standard contacts are provided for in these N. E. C. specifications, the ferrule clip for capacities up to 60 amperes, and the knife-blade contact for capacities from 60 amperes to 600 amperes, both for 250 and 600 volts. Fig. 4 shows a 600-volt, 30-ampere fuse with ferrule-clip contact, and Fig. 5 shows a 600-volt, 75-ampere fuse with knife-blade contact. The figures also show how each fuse is placed in its cut-out block.

The National Electric Code specifies the following as to the rating of enclosed fuses: "Fuses must be so constructed that with the surrounding atmosphere at a temperature of 75° F. they will carry indefinitely a current 10 per cent greater than that at which they are rated, and at a current 15 per cent greater than

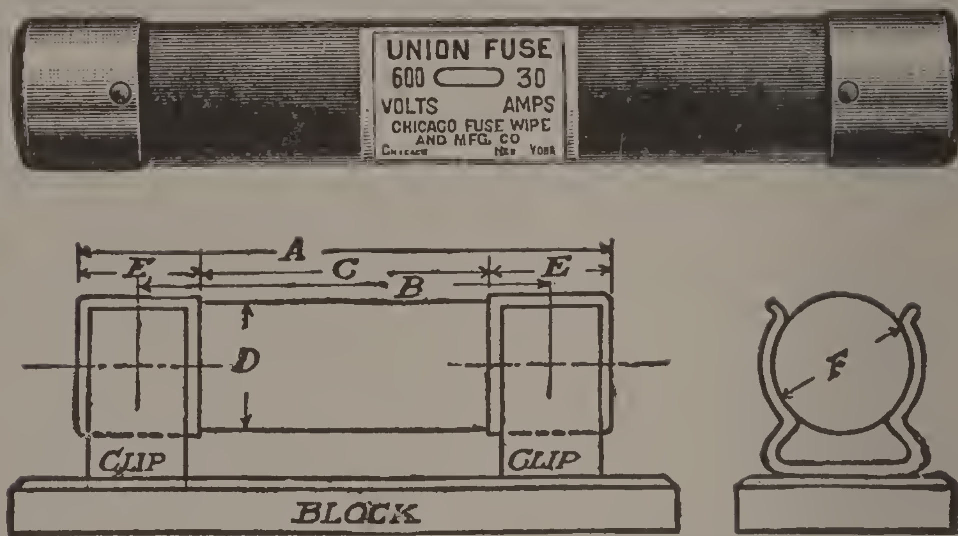
UNION FUSE
600 30
VOLTS AMPS
CHICAGO FUSE WIRE
AND MFG. CO
A
E
C
B
E
D
F
CLIP
CLIP
BLOCK

Fig. 4.

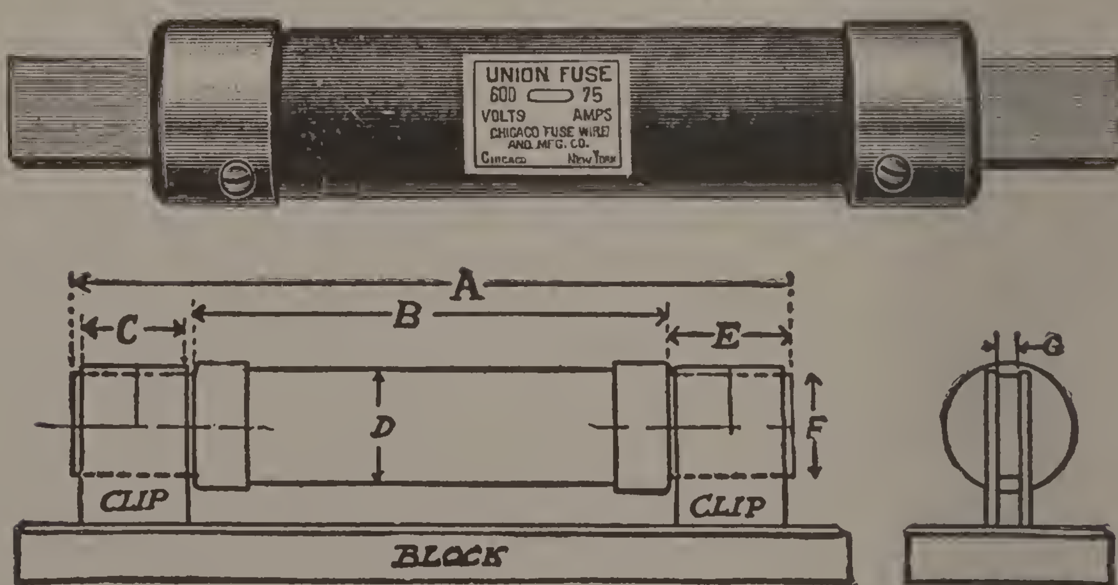
UNION FUSE
600 75
VOLTS AMPS
CHICAGO FUSE WIRE
AND MFG. CO.
CHICAGO NEW YORK
A
B
C
E
D
F
G
CLIP
CLIP
BLOCK

Fig. 5.

the rating they will open the circuit without reaching a temperature that will injure the fuse tube or terminals of the fuse block. With a current 50 per cent greater than the rating and a room temperature of 75° F., the fuses, starting cold, must blow within the time specified:

"0- 30 amperes	1 minute.
31- 60 amperes	2 minutes.
61-100 amperes	4 minutes.
101-200 amperes	6 minutes.
201-400 amperes	12 minutes.
401-600 amperes	15 minutes."

To make a fuse that will satisfy these conditions as to rating is one of the difficult points of manufacture. However, the manufacturers are now producing fuses which meet the requirements of the National Board of Fire Underwriters in this particular.

From time to time attempts have been made to produce a refillable enclosed fuse; that is, one in which the fuse element may be replaced after it has blown and the tube or cartridge refilled with the filling powder. There are many difficulties to be overcome in the design of a dependable refillable fuse, although in time they may be overcome. In the past the attitude of the Fire Underwriters toward the refillable fuse has generally been one of disfavor.

One form of fuse not yet mentioned here is the well-known Edison fuse plug. It is used with currents up to 30 amperes on circuits where the potential does not exceed 125 volts. It has a wide application in electric-lighting circuits, where the ease with which it may be inserted and its reliability make it especially valuable.

The importance of the fuse as an electrical safety device can not easily be overestimated. When properly made and in good condition, it is a reliable safe-

guard against damage due to excessive current. For this reason it should be regarded as one of the best friends of the electrician and the engineer, and not as a necesary evil. When a fuse blows out, replace it with another of the same capacity. False ideas of economy should never be allowed to dictate the use of a fuse of greater capacity than the conditions require. It is needless to say that copper wire or a nail should never be used, and yet one sometimes sees the cut-out block rigged up in this way, in the absence of a fuse. Such a practice is bad engineering and may prove to be worse economy.

Questions and Answers.

Q. What is the chief source of danger to electrical equipment?

A. Greater current than the apparatus is designed to stand.

Q. What two effects of the current are made use of in protective devices?

A. The thermal or heating effect, and the magnetic effect.

Q. What protective device depends upon the thermal effect?

A. The fuse.

Q. What device depends upon the magnetic effect?

A. The circuit-breaker.

Q. Of what did the first fuse consist?

A. A small piece of copper wire.

Q. Why was this unsatisfactory?

A. Because of the high melting point of copper.

Q. What material was then used?

A. Lead and its alloys.

Q. What objection was there to this fuse?

A. The danger from molten lead when the fuse blew.

Q. Who patented one of the first enclosed fuses?
A. Edison, in 1880.
Q. Of what did the fuse consist?
A. Merely a lead wire enclosed in a sheath or tube.
Q. What was the next step in the evolution of the enclosed fuse?
A. Filling the tube with an inert powder.
Q. What is an indicator in an enclosed fuse?
A. A device to show when the fuse is blown.
Q. Of what does this device consist?
A. A small wire shunted across the main fuse and brought near to a small hole in the tube. When the shunt wire is burned out that fact can be noted through the hole.
Q. Of what material are the tubes made in the best fuses?
A. Vulcanized fiber.
Q. What kinds of contacts are used in N. E. C. standard fuses?
A. Ferrule clip and knife blade.
Q. Are fuses and cut-outs from the different manufacturers made according to standard specifications?
A. Yes; N. E. C. specifications.

CHAPTER II.

One of the most important and widely used safety devices in the electrical field is the **circuit breaker.** It is made in a variety of forms to meet the different abnormal conditions which may arise in an electric circuit, any one of which may be destructive to the equipment served by the circuit. These abnormal conditions include short circuit, grounding, overload, underload, low voltage, current reversal, and phase reversal in alternating current. Perhaps the most common condition which the circuit breaker is used to guard against is an excessive flow of current, caused by short circuit, grounding, or overload. Such an excessive flow of current will damage the equipment connected to the line, and it is the function of the breaker to open the circuit before the excessive current has time to do damage.

Unlike the electric fuse, which depends upon the heating effect of the current for its action, the circuit breaker is operated by the **magnetic action** of the current. Practically all breakers are provided with a heavy series coil, through which the total current of the line passes. The core of this coil is magnetized by the action of the current, the magnetization increasing as the current increases. A soft-iron armature is attracted toward this magnet, and thus the pull on the armature becomes proportional to the current flowing in the magnetizing coil. Whenever the current exceeds a certain safe limit the armature is drawn to the magnet, and this motion releases a trigger which holds the breaker in the closed position against the

action of a strong spring. As soon as the trigger releases the spring, the breaker is opened suddenly, thus breaking the circuit.

It will be evident that as long as all other conditions remain constant, the amount of current required to operate the breaker will vary with the distance between the pole of the magnet mentioned above and its soft-iron armature. As the distance between magnet and armature increases, the magnetic pull on the armature becomes less for the same current in the coil. Hence to provide enough pull to move the armature, the current in the coil must be increased. The armature may be moved by means of an adjustable stop, and hence it is possible to set the breaker to operate at any current within its capacity. To set it to operate at high current, move the armature away from the magnet, and to operate at low current set the armature closer to the magnet.

In considering the **structural details** of some of the most widely used circuit breakers, let us study first of all the simple overload single-pole breaker. This device is designed to open the circuit whenever an abnormal flow of current, due to overload or any other cause, occurs. It will operate instantly whenever the current becomes excessive, without regard to the **duration** of the overload. Such a breaker is shown in Fig. 6, from which a good idea may be obtained of its construction and operation.

The movable armature is shown at 127, and the pin upon which it is pivoted at 128. The magnet 59, energized by the winding 50A, exerts a pull on the armature 127. When the breaker is closed the armature is held by gravity away from the magnet 59 and against a stop 136, which may be adjusted by the knob 11. When the current exceeds the limit for which the breaker is set, the armature 127 is drawn against the magnet 59, revolving on its pivot pin 128. When

making this motion the armature strikes the latch or trigger 87, which in the normal position holds the breaker closed against the action of the springs. When

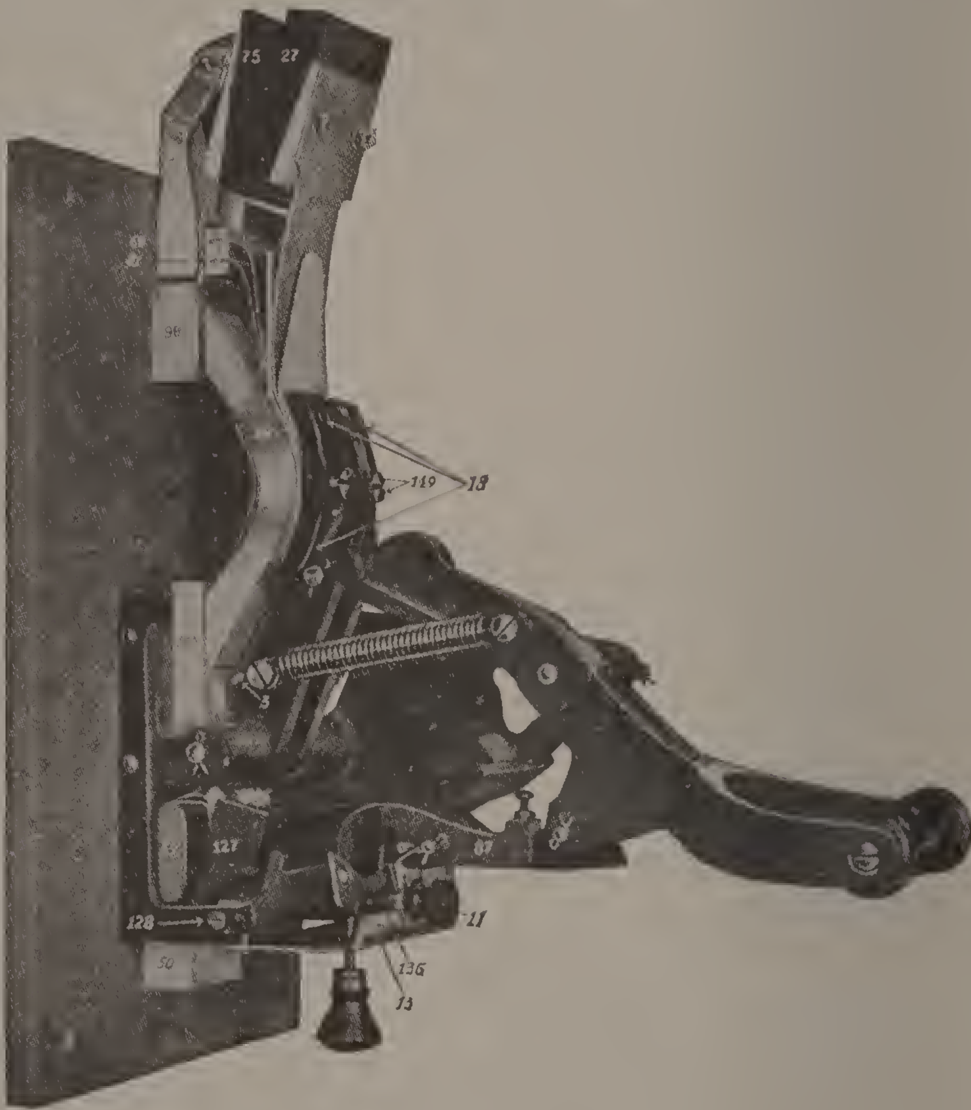

Fig. 6.

the latch 87 is thrown out of engagement by the action of the armature 127, the breaker is instantly opened by the action of the springs.

When a circuit carrying a heavy current is broken, an intensely hot arc is formed which is very destructive to metal contacts or terminals. It therefore be-

comes necessary to protect the main contact points of the circuit breaker from the effects of the arc. This is done by using auxiliary contacts of carbon where the final break is made. A further consideration of Fig. 6 will show how this is done.

The instrument has two fixed terminals, 98 at the top and 50 at the bottom. These terminals are connected to studs which come through the switchboard from the rear, to which the main leads from the generator are attached. The current enters the instrument at the lower contact 50, then passes through the overload coil 50A, and into the contact block 50B. Then it passes through the laminated copper bridge 16, thence to the upper contact block 98, through its connecting stud to the back of the switchboard, and out again on the line. A shunt circuit or by-pass of higher resistance than the main bridge 16 is formed by the copper strip 3. The current passes from the lower contact block through the copper strip 3 to the spring plate 30. From there it passes to the secondary metallic contacts 69 and 81, and finally to the carbon contacts 27 and 75.

When the circuit breaker operates the action is about as follows: The main bridge 16 first breaks contact with the upper block 98. This shunts the current through the secondary path formed by the strip 3 and the plate 30. This shunt circuit is a sufficiently good conductor to take the whole current and prevent the formation of an arc at the main contact between 16 and 98. Next the secondary contact between 69 and 81 is broken and the current passes to the carbon contacts 27 and 75, which up to this time have been closed. The final break occurs between the carbon contacts, which are able to stand the high temperature of the arc without much damage. In this way no arc is formed between metallic contacts and the life of the contact members is greatly increased.

Practically all electrical equipment is designed to take an overload of as much as 50 per cent, and sometimes more, provided it is not continued for any great length of time. Such a temporary overload occurs on motors which start under load, on feeder lines, where the load is variable, and may for a short time exceed the rated capacity of the line, and on generators supplying a number of lighting feeders where the load may be suddenly increased, as, for example, in the case of a thunderstorm, which causes the consumers to turn on their lamps. Inasmuch as the equipment is designed to take care of these temporary overloads without injury, it follows that the circuit breaker which protects the equipment must be designed to handle the overload without opening the circuit. It will be evident, then, that the simple overload breaker described above will not be able to meet this condition because it is designed to open the circuit instantly whenever the load exceeds the normal.

Consider, for example, the case of a generator which is designed to carry an overload of 50 per cent for one hour without injury. It is not at all likely that the machine would be able to carry the same overload safely if continued for five hours. Therefore the circuit breaker which protects this generator must handle an overload of 50 per cent for one hour, but must open the circuit if the overload is continued much longer than that.

The requirements which a circuit breaker must meet in this kind of service may be stated about as follows: On short circuit or very excessive overload it must open the circuit instantly. On overloads within the capacity of the equipment to handle, it must not operate unless the overload be of long duration. When the overload is continued for a length of time sufficient to endanger the safety of the equipment, the breaker must open the circuit. In short, the in-

strument must be affected not only by the **magnitude** of the overload, but also by its **duration.**

Several different circuit breakers have been devised which embody this time-element feature. One of the best of these designs which has come to the notice of the writer is shown in Fig. 7. The main features of

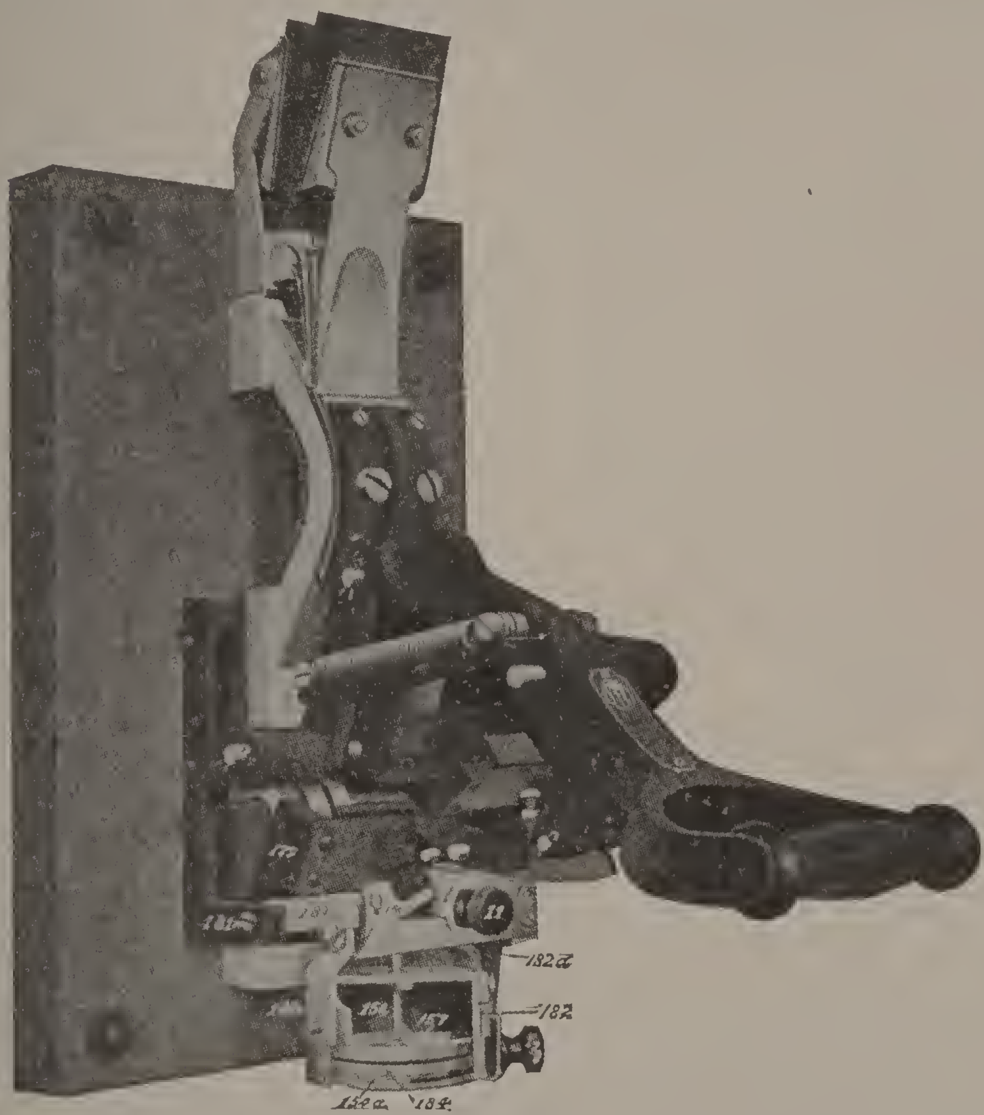

Fig. 7.

this breaker are practically the same as the simple overload breaker shown in Fig. 6, with the **addition** of the time-element feature. Below the housing of

the instrument is placed a small cylindrical vessel 154. This vessel contains a specially prepared seat 154a, on which rests the disk 184. This disk has a stem 157, which is attached to the armature 179 of the tripping mechanism. Thus the little disk 184 is attached to the magnet which trips the breaker, and as the magnet moves it must lift the disk from its seat.

The manner in which the cylindrical vessel containing the disk is supported is of importance. It is held in position by a surrounding ring 182, which has two lugs 182a, one on each side. These lugs are connected to the arms 187 of a frame which is pivoted on the pin 181 which supports the armature. The two arms, each marked 187, carry a plate 156, which cooperates with a projection of the knob 11. By moving the knob 11 to the right or to the left along the calibration plate 13, the vessel 154 is raised or lowered, and at the same time the armature 179 is moved toward or away from its magnet. Thus the overload setting of the breaker can be changed by moving the knob 11 on the calibration plate 13.

The vessel 154 contains a small quantity of special oil, which surrounds the disk and its seat, thus excluding all air from between the contact surfaces, which are separated only by a very thin film of oil. The surface tension of this oil film causes the disk to adhere to its seat, so that a considerable pull is required to separate them.

The operation of this time-element feature is as follows: When an overload occurs, the pull of the armature tends to lift the disk from its seat, thus subjecting the oil film to tension. If the overload be continued for a considerable time the pull will finally rupture the oil film, the disk will be lifted from its seat, the armature is attracted to its magnet and the breaker is tripped, opening the circuit. In the case of a short circuit or very heavy overload, the pull of

the armature is sufficient to rupture the oil film at once, and the breaker operates instantly.

In order to pull the disk from its seat it must be moved a certain small distance against the surface tension of the oil film; that is, a certain definite amount of work must be done. A comparatively small overload, long continued, pulls steadily on the disk, until finally the oil film breaks. If the overload is relieved before rupture occurs, the pull on the disk becomes less, and it falls back on its seat again. Thus a breaker like this meets the conditions of operation outlined above. It is known as the inverse time-element circuit breaker, because the time required to trip it is inversely proportional to the magnitude of the overload.

When two or more generators are operating in parallel a condition may arise which neither the overload circuit breaker nor the time-element instrument is able to meet. In case of accident to one generator or to its prime mover it may not only fail to deliver its portion of the power but may even draw current from the line and thus operate as a motor. Hence a reversal of current in the generator circuit must be guarded against. The same condition may arise in connection with rotary converters, storage batteries and charging sets.

In order to meet this condition a reverse-current circuit breaker has been designed, which operates when the current in the circuit reverses, and thus throws the machine out of circuit. Fig. 8 shows a breaker of the ordinary overload type, provided with the time-element feature and also having the reverse-current attachment. Such a breaker will protect against sudden heavy overload, continued overload and reverse current. The reverse-current relays are shown at the bottom of the instrument, Fig. 8.

The two coils shown in the figure are connected as

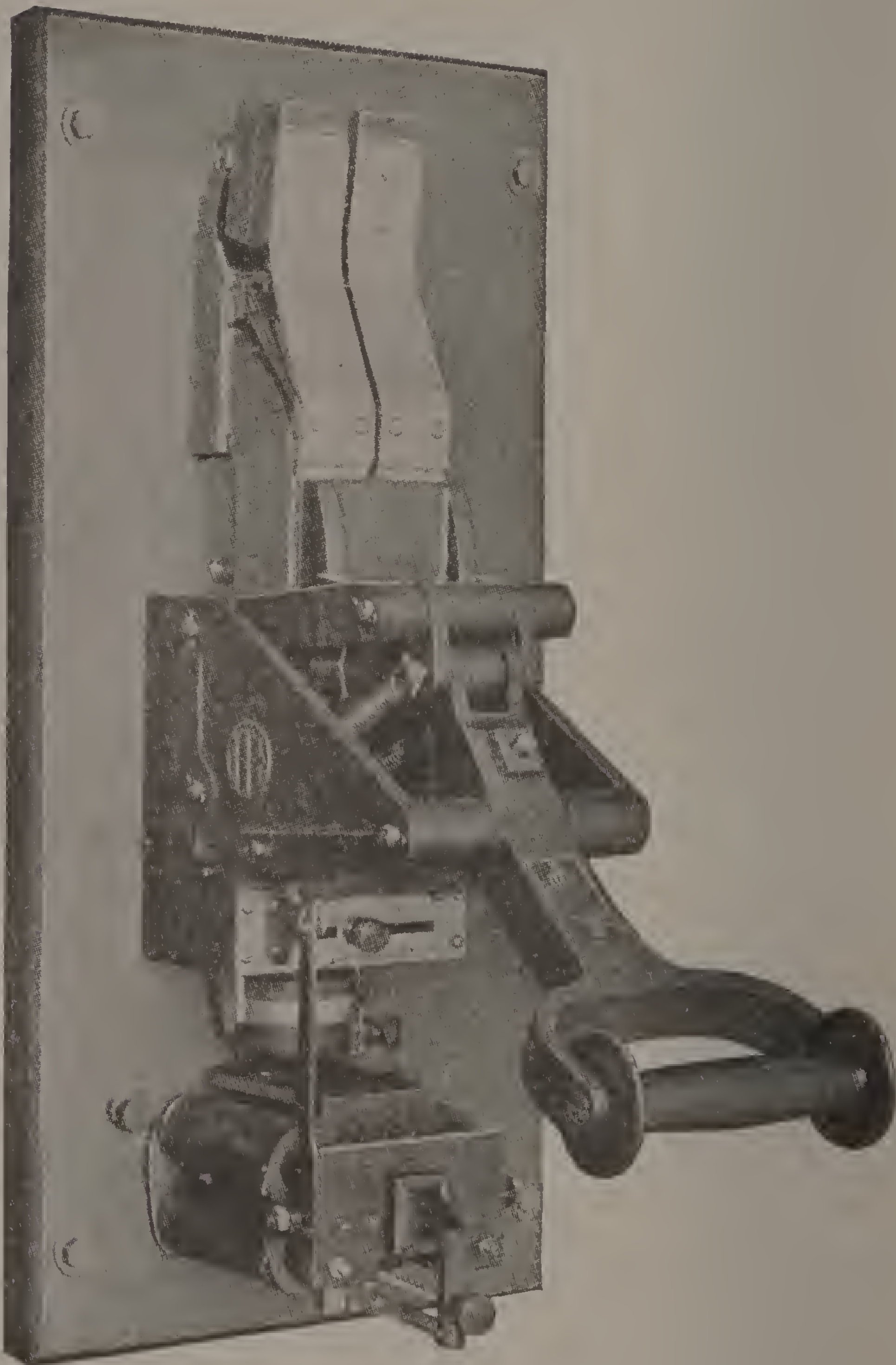

Fig. 8.

shunts to the main circuit and are wound in opposite directions, giving them opposite polarity. Between the poles of these two shunt magnet coils is placed the pole of a magnet, energized by a series-wound coil. The core of the series coil is movable and may be attracted toward either core of the shunt coils. When the current flows in the proper direction the series coil and the lower shunt coil have opposite polarity and their cores are therefore attracted toward each other. When a reversal of current takes place the polarity of the series coil is reversed, while that of the shunt coils is unchanged. The core of the series coil is now attracted toward the upper shunt coil, and this motion trips the breaker. Thus the circuit is broken at the instant the current reverses.

Questions and Answers.

Q. Upon what effect of the electric current does a circuit breaker depend for its action?

A. Upon the magnetic effect.

Q. How is this magnetic effect made use of?

A. The circuit breaker is provided with a series coil; a soft-iron armature is attracted toward the core of this coil whenever the current becomes excessive. The motion of this armature trips a trigger and a spring opens the breaker.

Q. What is the simplest kind of circuit breaker?

A. One which provides protection against excessive current, due to short circuit or heavy overload.

Q. Is such a breaker always satisfactory?

A. No; it is often desirable to carry a small overload for a time and the overload breaker would open the circuit.

Q. What kind of a breaker is used in such a case?

A. A time-limit breaker, which opens the circuit in a time inversely proportional to the magnitude of the overload.

Q. Will such a breaker operate instantly on short circuit or dangerous overload?

A. Yes.

Q. What usually occurs when a circuit carrying a heavy current is broken?

A. An arc is formed.

Q. How is a circuit breaker made to prevent damage to the metallic contacts by the action of the arc?

A. Auxiliary carbon contacts are used, and the final break is made there.

Q. What is a reverse-current breaker?

A. One which opens the circuit when the direction of current flow is reversed.

Q. Where is such a breaker used?

A. On generators running in parallel, on storage batteries, and on battery-charging sets.

Cuts supplied through courtesy of the Cutter Company.

CHAPTER III.

Lightning Arresters.

An important line of electrical safety equipment has been developed for the protection of overhead transmission lines, designated by the general term "lightning arresters." Used in this connection, the word "lightning" means much more than is implied in the popular definition of the term. It may be taken to mean any abnormal condition of voltage or frequency, produced by external or internal causes, tending to interfere with the proper operation of the system.

Some of these conditions, which are all grouped under the one term "lightning," are as follows:

1. An electric discharge between a cloud and the earth which strikes the transmission line. This is lightning in the ordinary meaning of the term.

2. The induction, on the transmission line, of an electrostatic charge of high potential from a heavily charged cloud. This charge may or may not be sufficient to produce a discharge between the cloud and the line.

3. The gradual accumulation of a charge upon the line from rain, snow or mist. This occurs particularly during a thunderstorm when the raindrops all carry a static charge.

4. Pressure disturbances due to sudden changes in the load, such as throwing machines on or off.

5. Surges and oscillations on the line, the initial

cause of which can probably be traced to short-circuits, grounds, discharges at faulty insulators, etc.

All of the phenomena enumerated above produce high potential charges upon the line, which in time may become sufficient to cause a discharge to the earth or any other adjacent object. As soon as the discharge takes place with the formation of an arc, the dielectric resistance of the air is greatly reduced, which makes it possible for the arc to be maintained at a potential difference much less than that at which it was started. The result is that a virtual "ground" is produced by the arc unless something is done to interrupt it.

To meet this condition one of the first lightning arresters that ever came into practical use was invented by Prof. Elihu Thomson in 1884. The idea of this arrester can be seen from Fig. 9, which shows an outline of the essential parts. The overhead transmission line is shown at L; aa is a single gap across which the charge must arc in order to find its way to the ground G. M is an electromagnet energized by the coil C, through which any current following a static discharge between the terminals aa must pass on its way to the ground. The result is that the arc is immediately blown out by magnet M, in the field of which the arc was originally formed. Thus this device allows a heavy static charge to escape to the earth, but will not permit much current to escape because the magnet blows the arc out.

It may be of interest at this point to consider just what is the action of this magnet in blowing out the arc. In the first place it must be remembered that the arc can only be maintained by the flow of current across the gap between the two terminals. That is, the gap is really a conductor carrying a current, although, of course, the resistance is very high. We have then in the case of the blow-out magnet, a con-

ductor carrying a current at right angles to a magnetic field. Now the fundamental principle of the electric motor is that a conductor carrying a current

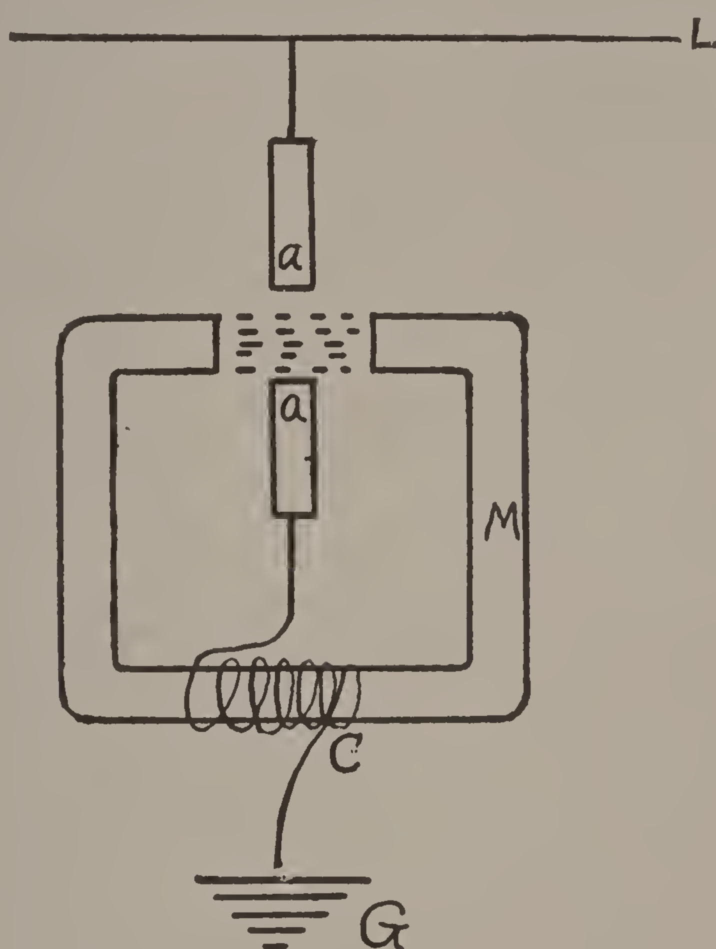

FIG. 9.

and so placed with respect to a magnetic field is **moved across the lines of force.** When this particular conductor is moved across the lines of force it is bent more and more, since the terminals aa can not move, until finally it is broken and the arc extinguished.

This type of lightning arrester is now used considerably in direct-current work, where the pressure does not exceed 6,000 volts. The length of the spark

gap is usually made adjustable so that it can be used for different voltages.

The magnet blow-out also has considerable application in electric railway work, where it is used to blow out the arc formed when contacts are broken in the controller. Every time the motorman starts the car, sliding contacts are made and broken and the contact strips and fingers would be greatly damaged by the arc if provision were not made to blow it out. The coil of the blow-out magnet is connected in series so that the strength of the magnetic field varies with the strength of the current which must be interrupted.

When we come to transmission lines of high potential the single-gap arrester with magnetic blow-out is no longer satisfactory. To meet this condition the multigap arrester is used perhaps more widely than any other. It consists of a number of small brass cylinders, mounted in a row on an insulated base with small gaps between them. The cylinder on one end of the row is connected to the transmission line, and the one at the other end connected to the ground. The action of this arrester is about as follows:

These little cylinders are all charged inductively from the line, the intensity of the charge on each being proportional to its distance from the line. That is, the one nearest the line will have a maximum charge and the one nearest the ground will have practically a zero charge. When the potential difference between the first and second cylinders becomes sufficient to break down the resistance of the intervening air a discharge takes place between them. The second cylinder is now connected to the first by means of the arc, and its potential may be raised sufficiently to produce a discharge between it and the third. In the same way the discharge may continue from the third cylinder to the fourth, and so on, until all the gaps have been bridged. The charge then escapes

to the ground and current begins to flow through the successive arcs from the line to the ground. There is now a uniform drop in potential across the arrester from a maximum at the line to zero at the ground. The potential necessary to maintain the arc is less than was required to start it because of the weakening of the dielectric resistance of the air due to the heat of the arc.

The arc across the arrester might therefore continue for a considerable time, except for one important fact. An alternating e. m. f. passes through the value zero twice in each complete cycle. After the high-potential charge has dissipated itself in the arrester or has escaped to the ground there will be insufficient potential to form the arc again after it has gone out at the end of a half cycle. Thus in this case no magnetic blow-out is needed, because the arc puts itself out when the e. m. f. becomes zero.

The behavior of a multigap arrester is somewhat affected by the frequency. As the frequency increases, the potential at which the arrester will discharge decreases. In order to make an arrester which will work satisfactorily on different frequencies, resistances are connected in shunt with the gaps as shown in Fig. 10. In the figure, R_1 is a low resistance shunted across a portion of the gaps; R_2 is a somewhat higher resistance shunted across still more of the gaps, and R_3 is a high resistance connected across almost the whole of the arrester. The action of a multigap arrester with shunt resistances as shown is about as follows:

In the case of high frequency the discharge can pass more readily across the gaps than through the shunt resistance, hence it will take the direct path across the arrester. The fact that self-induction of the resistance increases with the frequency is another reason why a high-frequency discharge passes across the

arrester gaps instead of through the shunt resistance. When the frequency is lower the discharge passes through the low resistance R_1 and then across the gaps to the ground; if the frequency is still lower

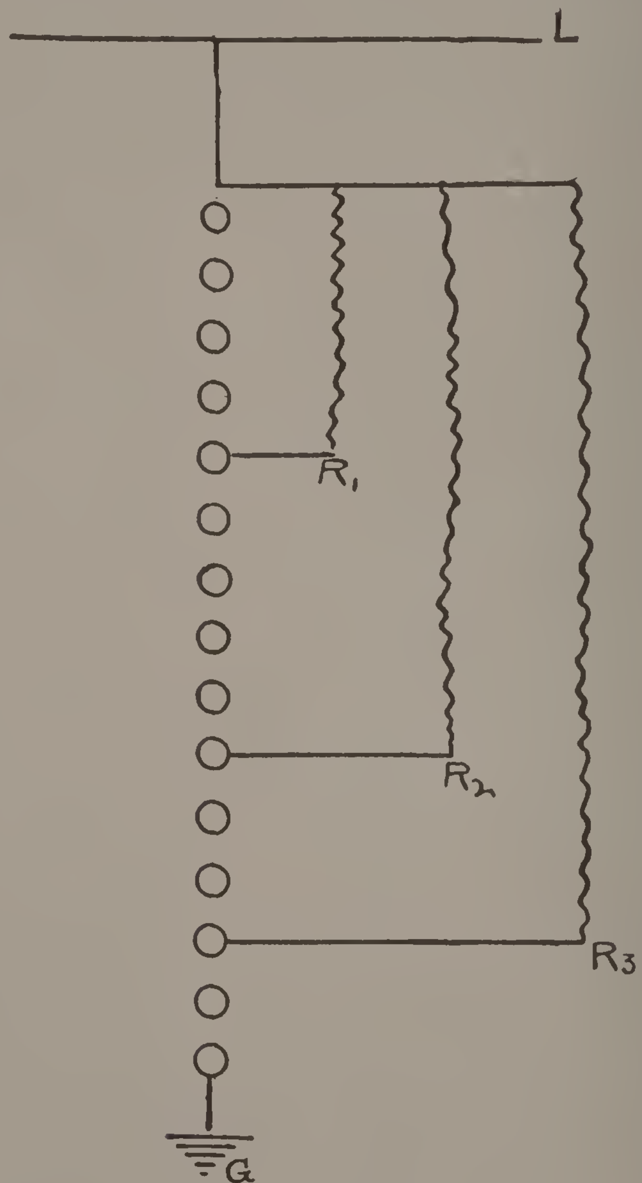

FIG. 10.

the discharge passes through the intermediate resistance R_2 and then across the remaining gaps. Finally, in the case of a still lower frequency it passes through the high resistance R_3 and then across the few remain-

ing gaps. Thus such an arrester provides protection against high-potential disturbances of almost any frequency.

It must not be supposed that the only frequency which may occur on a transmission line is the normal frequency of the system as determined by the generators. Lightning disturbances may produce on a transmission line very high frequency oscillations, many times the normal frequency. On the other hand, sudden changes in load, short circuits, grounds, etc., may produce a swinging or surging of the power on the line which is of relatively low frequency. Hence a lightning arrester may have disturbances to guard against, the frequencies of which vary through a wide range.

In some cases a resistance is connected in series with a multigap arrester, although it is not usually considered good practice. A resistance in series will cut down the current flowing across the arrester and so prove a protection to the latter. But in the case of a very high-frequency disturbance the inductive action of the resistance would choke back the current and so prevent the arrester from operating. In general, series resistances are not used.

It sometimes happens that a high-frequency oscillation will enter a generating station and do damage to the equipment even although the system be supplied with lightning arresters. In such cases the damage is done before the lightning arrester has time to operate. To meet such a condition as this, reactance coils are connected into the line where it enters the station. Part of the wave is reflected by the reactance coil and then finds its way to the earth through the lightning arrester. Part of it will, of course, pass through the coil, but it must not be enough to break down the insulation of the station equipment. Thus if the coil is properly designed it protects against

high-frequency disturbances. On the other hand, it affords no protection against low-frequency surges, because the reactance of the coil must be limited to that allowable for the normal voltage of the line.

Questions and Answers.

Q. What is a lightning arrester?

A. A device to protect a transmission line and the equipment connected thereto from lightning.

Q. What is the meaning of the term lightning as used in this connection?

A. Any abnormal pressure condition, whether produced for external or internal causes.

Q. What are some external causes which may produce such a condition?

A. A direct stroke of lightning striking the line; the induction of a heavy charge upon the line from a near-by cloud; or the accumulation of a charge from rain, snow, etc.

Q. What are some internal causes which may produce a similar condition?

A. Sudden changes in load; a short-circuit; a ground; a discharge from a lightning arrester, etc.

Q. Who invented the first lightning arrester to come into extensive practical use?

A. Prof. Elihu Thomson, in 1884.

Q. Of what did this arrester consist?

A. It consisted of a single spark gap with magnetic blow-out.

Q. How was it connected to the line?

A. One side of the gap was connected to the line, the other side to the ground, with the coil of the blow-out magnet in series with the gap.

Q. What is the purpose of the blow-out magnet?

A. To blow out the arc formed by a discharge across the gap.

Q. How is this done?

A. The arc, which is a conductor, is at right angles to the field of the magnet. The arc is moved across the field, just as any conductor carrying a current would be, until it is broken.

Q. For what kind of work is this arrester used?

A. For direct currents up to 6,000 volts potential.

Q. For high-potential alternating-current work what kind of arrester is used?

A. The multigap arrester.

Q. How is it made?

A. It consists of a number of small cylinders of brass or special alloy, mounted close together but not touching, on an insulated base.

Q. How is it connected to the line?

A. One end is connected to the line, the other to the ground.

Q. How does such an arrester work?

A. The discharge forms an arc from one cylinder to the next, and so on, until the charge is dissipated in the arrester or escapes to the ground.

Q. Why is no blow-out magnet needed with this arrester?

A. Because an alternating e. m. f. passes through zero once in each half cycle. When this occurs the arc goes out, and the potential is not sufficient to start it again.

Q. What is the value of a reactance coil as a protective device on a transmission line?

A. On account of its reactance the coil throws back a high-frequency disturbance, which may then escape to the ground through the lightning arrester.

Q. Where are these coils placed on the line?

A. Near the station, to protect the equipment.

Q. Will such a coil protect from low-frequency disturbances?

A. No; the reactance is not sufficient; if increased, the reactance would interfere with the normal operation of the system.

CHAPTER IV.

Regulators.

A regulator is a device for controlling the voltage either at the generator or on a feeder near the center of distribution. Although, strictly speaking, the voltage regulator is not a safety device, still it partakes of the nature of such equipment, particularly when it is automatically operated.

In any large electrical distributing system it is impossible to have satisfactory voltage regulation at all points simply by control of the generator voltage at the central station. Some feeders may be long, while others are short; the load on one may be fairly uniform, while on another it may be subject to wide variations. Hence it becomes necessary to control the voltage on each individual feeder if the regulation is to be satisfactory at all times at all points of the system.

To meet this condition, feeder regulators have been devised which may be placed at any desired point on each individual feeder. These regulators are simply transformers or compensators, in which the ratio of transformation is variable by changing the number of turns of wire in circuit in the secondary winding. These regulating transformers are connected with the primary winding across the circuit to be controlled and the secondary in series with it.

Figs. 11 and 12 show diagrammatically the arrangement of the windings and the manner in which they are connected into the line. Fig. 11 shows a regulator

arranged to boost the voltage of the line, and Fig. 12 shows one which is arranged in such a way as to lower the line voltage. Of course, the same regulator is capable of both boosting and lowering effect.

In Fig. 11 the current in the primary or shunt coil

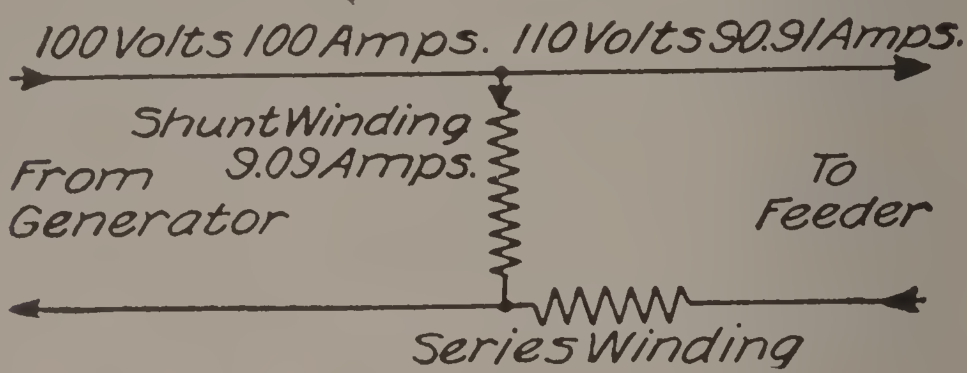

FIG. 11.

is in such a direction that it induces a pressure in the series or secondary coil in the same direction as the line pressure. This induced pressure is therefore added to the line pressure, which gives the regulator a boosting effect. In Fig. 12 the current flows in the

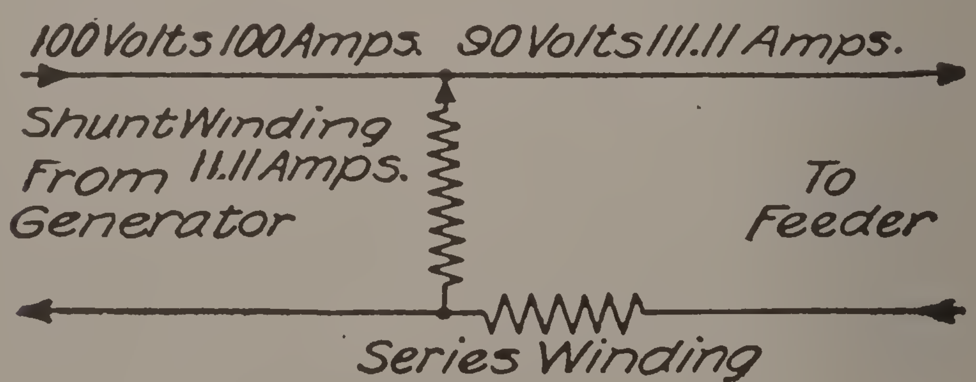

FIG. 12.

opposite direction through the shunt coil. This induces a pressure in the series coil which is opposite in direction to the line pressure. Thus the line pressure is reduced, giving the regulator a lowering effect.

The regulator shown in the figures is designed to have a 10 per cent boosting or 10 per cent lowering effect. That is, the windings are proportioned in such a way that the maximum voltage generated in the secondary by the inductive action of the primary is just 10 per cent of the line pressure. In this particular case a circuit of 100 volts and 100 amperes is assumed. In Fig. 11 the voltage boost is 10 per cent of 100 volts = 10 volts, and the line pressure beyond the regulator therefore becomes 100 + 10 = 110 volts. Now, before the regulator was reached, that is, to the left of the regulator in the figure, the total power on the line was 100 × 100 = 10,000 watts. Disregarding the slight loss which occurs in the regulator, the power is the same after the current has passed through it. Therefore the current beyond the regulator equals $\frac{10,000}{110} = 90.9$ amperes.

In Fig. 12 the secondary winding causes a reduction of 10 volts in the line pressure, which therefore becomes 100 — 10 = 90 volts. In this case the current beyond the regulator becomes $\frac{10,000}{90} = 11.11$ amperes.

This regulator is, of course, capable of any intermediate effect between 10 per cent boost and 10 per cent lower. This effect is obtained by reducing the number of turns of wire in circuit in the secondary coil, or by changing the position of the primary and secondary coils with respect to each other, which changes their mutual inductive effect. The well-known induction regulator produces its effect that way.

The induction regulator, like the one just described, has two windings, a primary across the line and a secondary in series with the line. Fig. 13 shows the arrangement of these windings. The primary or shunt coil is wound in slots on the outside circumfer-

ence of a movable iron core, and the secondary or series coil is wound in similar slots on the inside of a stationary iron core. The voltage regulation is obtained by changing the relative position of the primary and secondary coils by revolving the inner core. When a positive pole of the primary coil is opposite a positive pole of the secondary, a regular transformer action is produced and the voltage generated in the secondary boosts the line pressure. When a positive pole of the primary is opposite a negative pole of the secondary the voltage induced in the secondary is opposite in direction to what it was before, and the line pressure is therefore lowered. In a position of the movable coil midway between these two extremes the primary and secondary coils are out of inductive relation to each other, no pressure is induced in the secondary, and the regulator neither boosts nor lowers.

Perhaps a clearer idea of this action of the regulator may be obtained from the following considerations. The secondary coil, being connected in series with the line and wound on a stationary core, produces a flux which is constant in magnitude and direction. The direction of this flux is such as at all times to oppose the current which produces it. Now, whenever the flux from the primary opposes the secondary flux, it will induce in the secondary a voltage in the same direction as the line voltage, thus boosting the latter. This is just what takes place when similar poles on the primary and secondary coils are opposite each other. When unlike poles are opposite each other the effect is the reverse, as already explained. The whole effect is produced by these two fluxes, primary and secondary, acting against each other, with each other, or at some intermediate position between these two extremes.

By referring again to Fig. 13 it will be noted that the inside movable core has a short-circuited coil

wound at right angles to the primary shunt coil. The object of this coil is to decrease the reactance of the regulator, the principle of its operation being as follows: When the regulator is in the neutral, or no

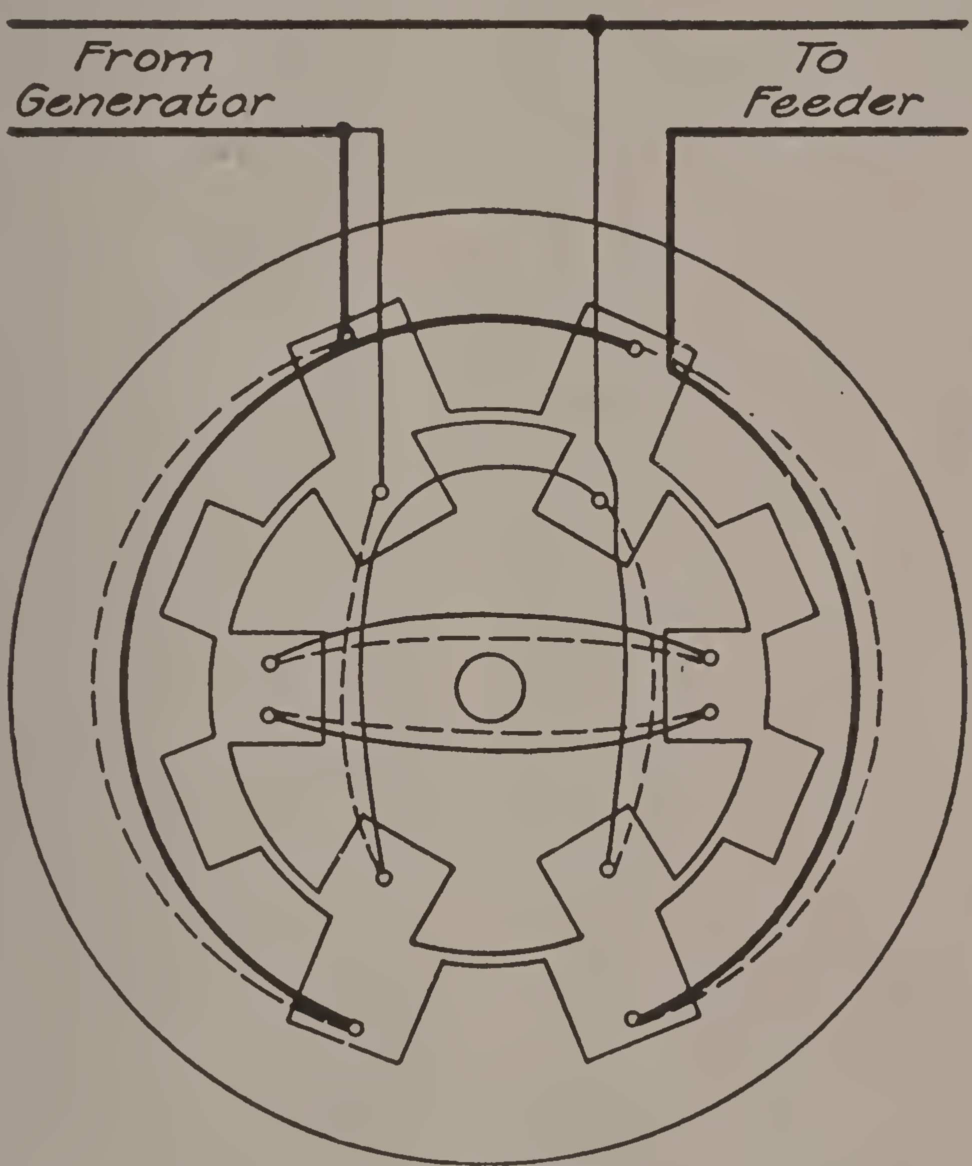

FIG. 13.

boost, no lower position, the primary and secondary coils are at right angles to each other, and hence have no mutual inductive relation. In this position none of the primary flux passes through the secondary, and

hence considerable potential would be required to force the line current through it; that is, through the secondary or series winding. This voltage would be at right angles to the line voltage, and hence a poor power factor would be the result.

The short-circuited coil, however, is in inductive relation with the secondary when the regulator is in the neutral position. The flux from the short-circuited coil, cutting the secondary winding, acts like a short circuit on the latter, and thus greatly reduces the voltage necessary to force the load current through it. Since the secondary is always in inductive relation with either the main primary winding or the short-circuited winding, it is always subject to more or less short-circuiting effect, which keeps the reactance down to a point where only a small amount of pressure is necessary to force the current through it.

Fig. 14 shows an external view of a single-phase induction regulator, the construction of which has just been described. The coils are mounted in an iron case very similar to that used for the ordinary transformer. Methods of cooling are practically the same as for transformers, but in many cases such a regulator operates satisfactorily when self-cooled.

The construction of a three-phase induction regulator is practically the same as the single-phase type, although the operation is somewhat different. The primary winding consists of three shunt coils, one across each phase of the system. The windings are arranged symmetrically in the slots of the inner movable core of the regulator, very much like the windings on a three-phase generator armature. For this reason the primary of the regulator is often spoken of as the armature. The flux produced by this three-phase primary winding is not constant in direction as in the case of the single-phase coil, but is revolving like the flux in the stator of an induction motor.

The series or secondary winding is arranged in slots on the inside of the stationary core, in the same manner as the primary. This winding consists of three separate coils, one for each phase. The volt-

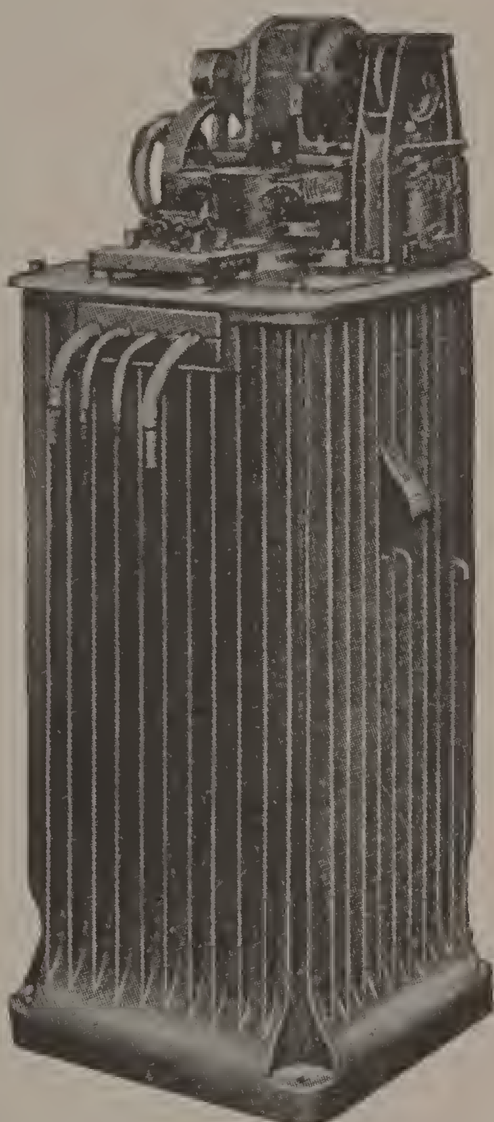

Fig. 14.

ages induced in the secondary are due to the revolving flux of the primary, produced by the combined action of the three phases. The secondary induced voltages are constant at all times and for any position of the

armature or primary, because the primary flux is constant in effect. The variations in the line voltage produced by the regulator are due to phase displacement between the secondary voltage and the line voltage.

Suppose that primary winding, phase 1, is just opposite the corresponding coil on the secondary. Then the action will be similar to the single-phase regulator and the voltage generated in this particular phase of the secondary will be added directly to the line voltage, giving a boosting effect. Now, if the primary coil be rotated slightly, phase 1 of the secondary will be acted upon by both phase 1 and phase 2 of the primary. This will produce a voltage in the secondary of the same magnitude as before, but somewhat out of phase with the line voltage. In this case the boosting will be less than before. Thus by rotating the primary any effect from maximum boost to maximum lower may be obtained.

Fig. 15 is a view of a three-phase induction regulator. The small motor on the top of the case is for revolving the regulator armature or primary. The control switch for the motor may be mounted on the switchboard, and the operator may boost or lower the feeder pressure simply by throwing the control switch up or down. A wheel for hand control is also provided, if for any reason the motor can not be used.

A regulator of this kind may also be automatically controlled, in which form it partakes of the nature of a safety device. This automatic control is accomplished by means of a contact-making voltmeter, shown in Fig. 16. This contact-making instrument consists essentially of a solenoid with a laminated iron core, both shown clearly in the figure. The core is supported by a spring and also by means of the current in the solenoid. The core of the solenoid operates a lever having contact points above and below.

Fig. 15.

With the voltage at the proper point the lever stands midway between the two contacts. A change in voltage causes a movement of the core of the solenoid, moves the lever up or down, and closes one or the other of the contacts. This operates a relay

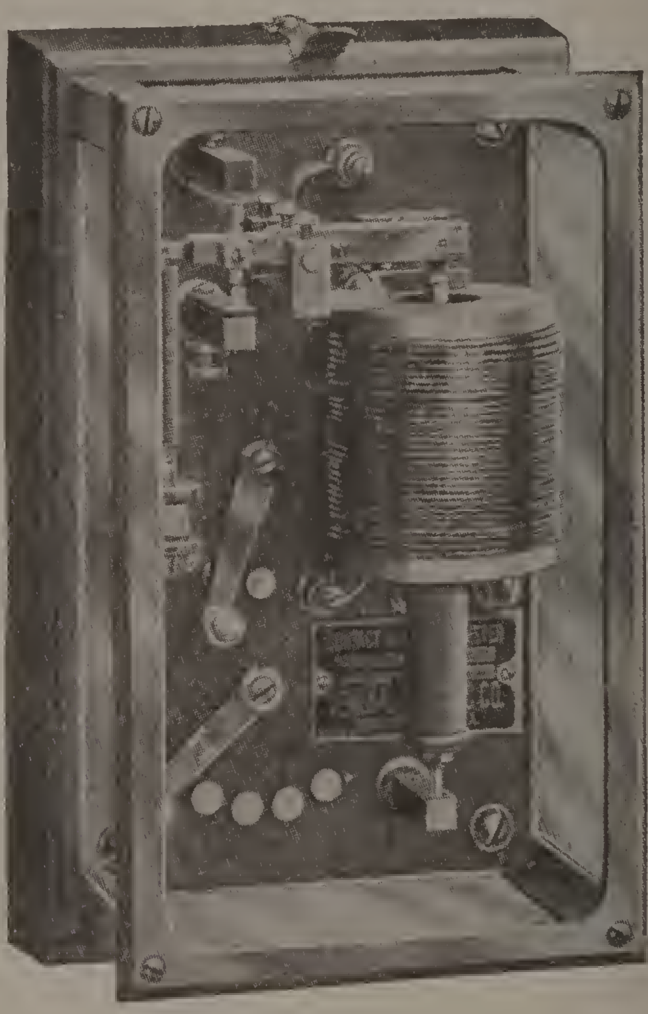

Fig. 16.

switch, which closes the circuit on the control motor of the regulator. When sufficient regulation has been obtained, the contact-making lever drops back again into the neutral position, the contact is broken and the motor stops. Thus the voltage regulation becomes entirely automatic.

Questions and Answers.

Q. What is a regulator?

A. A device for controlling the voltage of an electric circuit.

Q. Of what does an induction regulator consist?

A. It consists of two coils, a primary and a secondary, very much like a transformer.

Q. How are these windings connected?

A. The primary is shunted across the line, and the secondary in series with the line.

Q. How are these coils placed with respect to each other?

A. They are wound on concentric laminated iron cores, the primary on the outside of the inner movable core, and the secondary on the inside of the outer stationary core.

Q. How does such a device control the voltage of the line?

A. By means of the pressure induced in the secondary by the flux from the primary. This pressure is variable in amount and direction, depending upon the relative position of primary and secondary cores.

Q. How is a variable regulation accomplished with such a device?

A. Simply by turning the movable primary core inside the stationary secondary.

Q. How is this turning done?

A. By hand or with a motor.

Q. Can a regulator of this kind be automatically controlled?

A. Yes; by means of a contact-making voltmeter and relay switch.

CHAPTER V.

In Chapter IV it was pointed out that any automatic voltage regulator partakes of the nature of a safety device, since it guards against voltage fluctuations that might easily prove serious if allowed to go unchecked. There the different forms of induction regulators were discussed, and it was made plain that such an instrument is essentially a feeder regulator, designed to regulate the voltage on each individual outgoing line.

It is also very important, however, to have the generator in the power plant controlled by an automatic voltage regulator, so that the pressure will be maintained constant throughout all load fluctuations within the capacity of the machine. The instrument which probably has the widest application in this field is known as the Tirrill regulator, named after its inventor. This device is made for use with either direct or alternating current machines; in the case of the d. c. machine the regulator works by automatically short-circuiting the generator field rheostat, while in the case of the a. c. generator it short-circuits the exciter field rheostat.

Flg. 17 gives a diagram of the connections for a Tirrill regulator, designed for use with a d. c. machine. The essential parts of the instrument are the main control magnet and main contacts, shown in the upper left-hand corner of the drawing, and the differentially wound relay and relay contacts, shown at the right-hand side of the figure. The main control magnet is simply a solenoid provided with an iron core, and con-

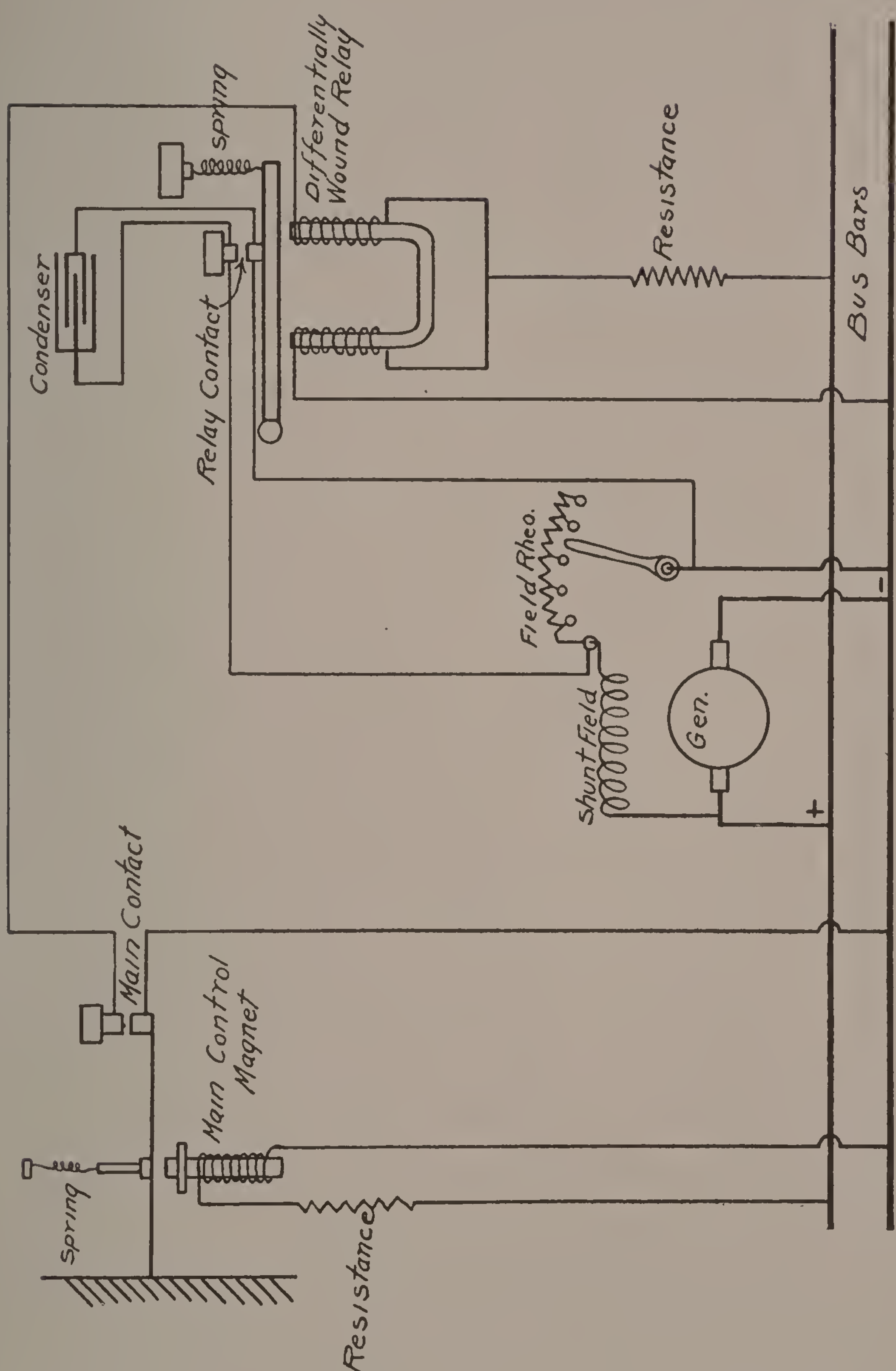
Spring
Differentially Wound Relay
Condenser
Relay Contact
Resistance
Bus Bars
Field Rheo.
Shunt Field
Gen.
+
-
Main Contact
Main Control Magnet
Spring
Resistance

FIG. 17.

nected permanently across the bus bars as shown. A coiled spring, shown above the main control magnet, opposes the action of the latter, and the two working against each other control the opening and closing of the main contact.

The two coils on the differentially wound relay are wound in opposite directions, so that the magnetism of one opposes that of the other. The left-hand coil of this relay will be seen from the figure to be connected permanently across the bus bars, while the right-hand coil is only in circuit when the main contact is closed. The action of the relay magnet is opposed by a coiled spring in practically the same manner as in the main control magnet. A condenser is connected across the relay contacts to reduce the sparking which might otherwise prove destructive at the opening of the contacts.

The drawing also shows the generator connected to the bus bars, the generator shunt field, and the field rheostat. It should be remembered that the regulator accomplishes its function by short-circuiting this field rheostat.

The action of the regulator is about as follows: Suppose that the generator voltage is about normal and that the main contact is open. Only the left-hand coil of the differential relay is receiving current, because the right-hand coil is not cut into circuit until the main contact is closed. Under this condition the differential relay holds the relay contact open against the action of the coiled spring. It will also be noted that generator field rheostat is in circuit with its machine.

Now, suppose that the generator voltage drops, due to increase in load. The coil of the main control magnet will now receive less current than before, because the pressure is less. Its pull will, therefore, become less and will be overcome by the spring above,

thus closing the main contact. As soon as this contact is closed, the right-hand coil of the differential relay is cut into the circuit. Since it is wound in the opposite direction from the left-hand coil, the magnetism of the former destroys that of the latter, and the pull of the relay becomes zero. The coiled spring above immediately pulls up and closes the relay contact. It will be seen from a study of the figure that as soon as the relay contact closes the field rheostat is short-circuited and thus thrown out of circuit. This immediately boosts the generator voltage, the main control magnet receives more current, which enables it to open the main contact. This throws the right-hand coil of the differential relay out of circuit, the relay contact is opened, which breaks the short circuit on the field rheostat, putting it into circuit again.

During the operation of such a regulator the duration of the short circuit of the field rheostat is very short. In fact, both main and relay contacts are constantly opening and closing.

Sometimes the main control magnet is supplied with a series coil in addition to the shunt coil. This series coil is connected in such a manner as to oppose the magnetism of the shunt coil. Thus, when the load becomes very heavy, the main control magnet becomes weak, due to the opposing action of the series coil. This enables the spring to keep the main contact closed for a longer time than would otherwise be possible, thus raising the voltage as the load increases. The effect is similar to that obtained from an overcompounded machine.

Of course, the series coil mentioned here does not receive the whole of the main current, but only a portion of it. A low-resistance shunt is connected in series with the line, and the series coil is then connected across this shunt, similar to the method used in connecting direct-current ammeters.

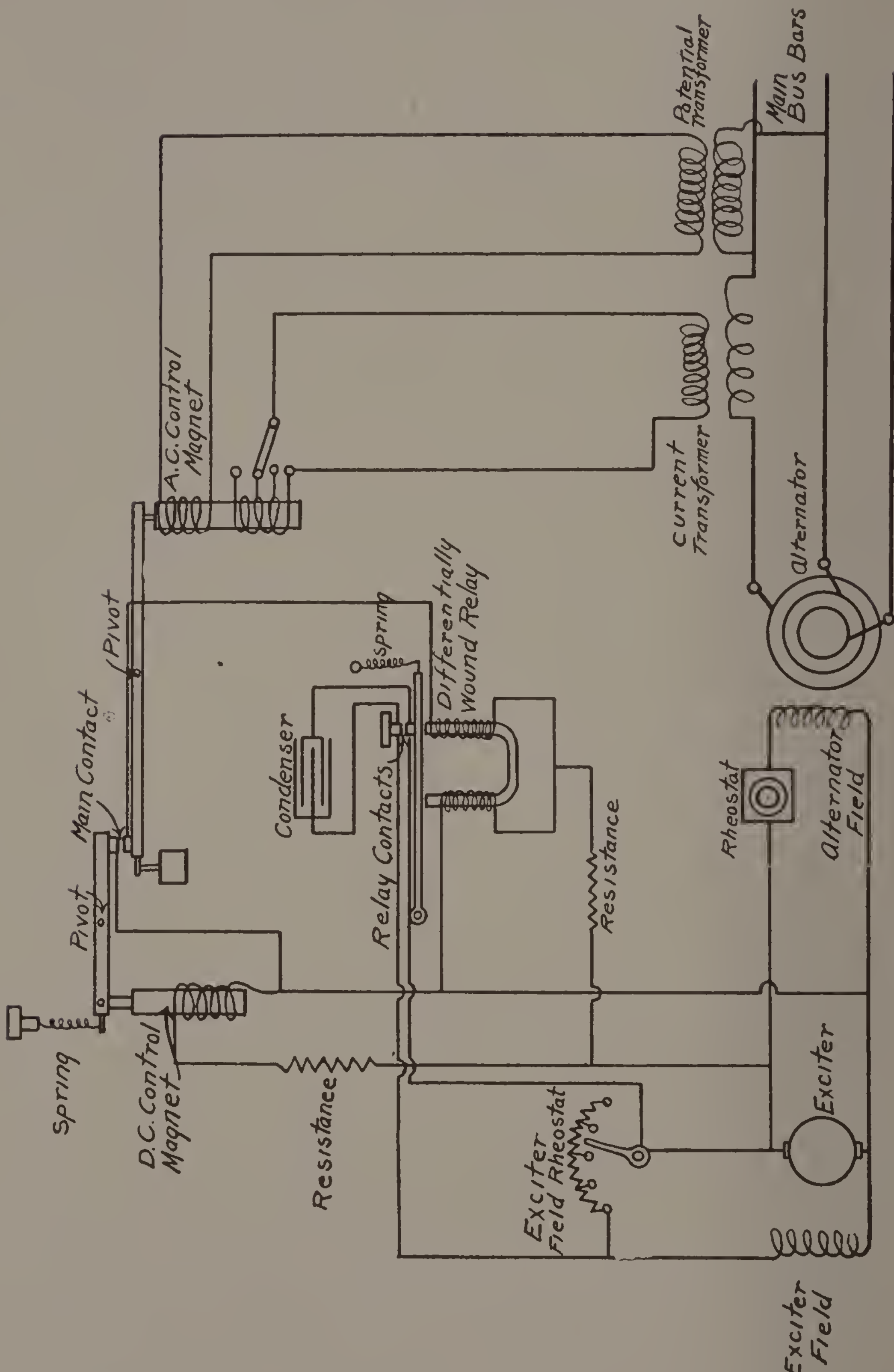
Potential Transformer
Main Bus Bars
A.C. Control Magnet
Current Transformer
Alternator
Pivot
Main Contact
Spring
Differentially Wound Relay
Condenser
Relay Contacts
Resistance
Rheostat
Alternator Field
Pivot
Spring
D.C. Control Magnet
Resistanee
Exciter Field Rheostat
Exciter
Exciter Field

Fig. 18.

Fig. 18 shows a diagram of the Tirrill regulator, as designed for use with an alternating-current generator. It will be noted that in this case the field rheostat of the exciter is short-circuited instead of the rheostat

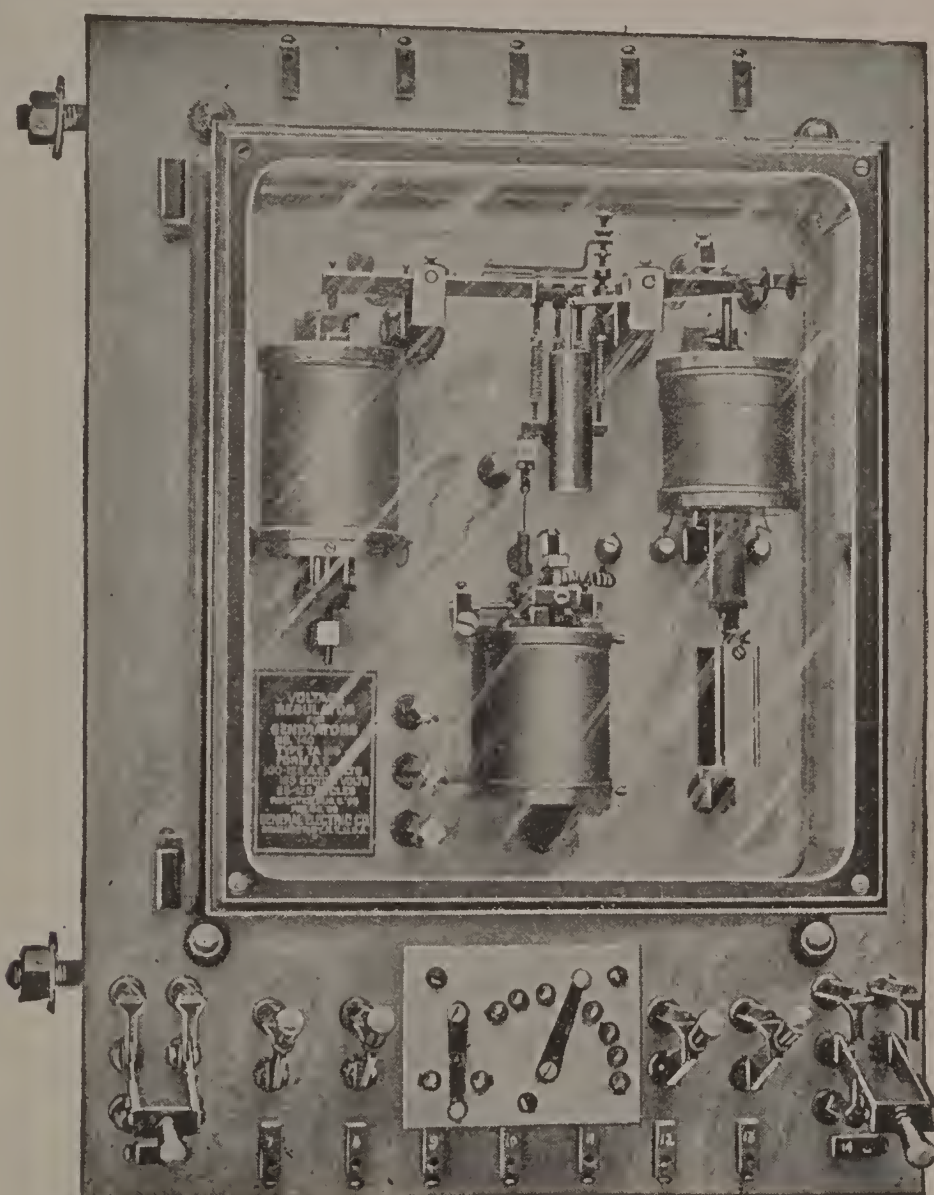

FIG. 19.

in the field of the machine itself. The regulator in this form operates in the same manner as the d. c. type, except that it is provided with an additional control

magnet, which is supplied with alternating current from the main bus bars. This alternating-current control magnet is shown in the upper right-hand corner or Fig. 18.

The operation of this magnet is as follows: It will be noted that it is provided with two coils, a series winding and a pressure winding. The former is supplied with current from a current transformer, the primary of which is connected in series with one of the main bus bars. The latter — that is, the pressure winding — is supplied by a potential transformer, the primary of which is connected across one phase of the main alternating-current circuit. Whenever the voltage on the a. c. side rises above normal, the a. c. control magnet receives more current and is drawn upward, due to its increased magnetism. This brings the main contacts farther apart, and so reduces the time of short circuit of the exciter field rheostat. In this way the normal boosting effect of the regulator is reduced somewhat.

The series coil of the a. c. control magnet is connected in such a way that its magnetism opposes that of the pressure coil, the result being to weaken the total pull of the magnet. When the load on the a. c. side becomes heavy, the differential effect of the series coil is increased and the a. c. control magnet becomes weaker. The effect is to permit of a longer closing of the main contact, which results in a longer duration of the short circuit on the exciter field rheostat. Thus an increased boosting or over-compounding effect is obtained by the action of the series coil on the a. c. control magnet, in practically the same way as has already been described for the d. c. control magnet.

Fig. 19 gives an exterior view of the Tirrill regulator fully assembled. The d. c. control magnet is at the left, the a. c. magnet at the right, with the main

contacts between them. At the bottom is shown the differential relay and relay contacts.

Questions and Answers.

Q. What is the function of a Tirrill regulator?

A. To automatically control the generator voltage.

Q. How is this control accomplished?

A. By short-circuiting the field rheostat.

Q. Can such a device be used for either d. c. or a. c. machines?

A. Yes; although there is a slight difference in design between the a. c. and d. c. regulator.

ALPHABETICAL INDEX

Alternating Currents Simplified

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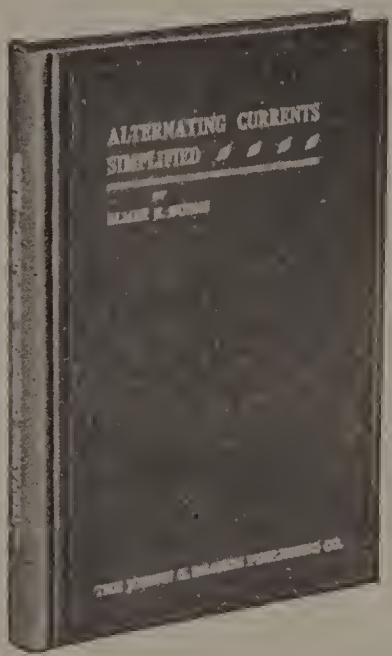
ALL ABOUT ALTERNATING CURRENTS



- How Alternating Currents Are Produced.
- What Is an Alternating Current?
- Magnetic Force of an Alternating Current.
- What Is Self-induction?
- What Is Capacity?
- Curve Tracing.
- Phase and Frequency.
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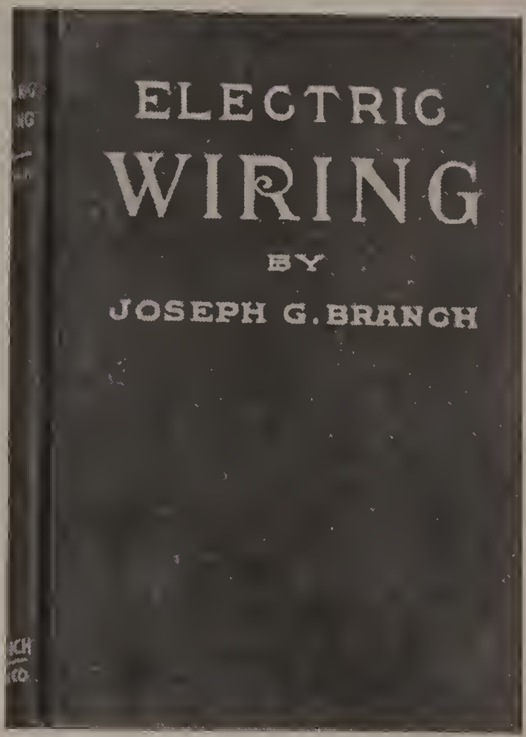

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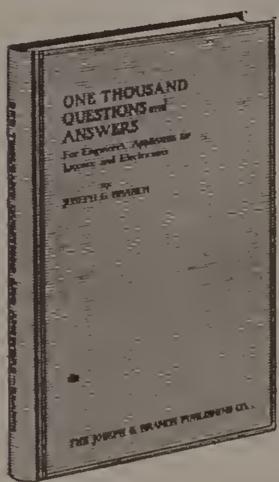

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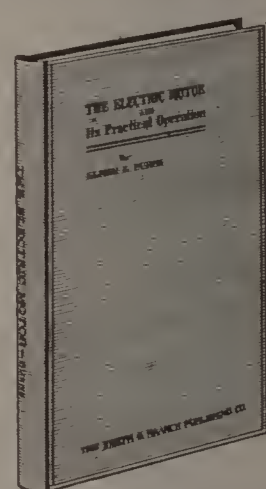

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